LA-UR-13-28381

Approved for public release; distribution is unlimited.

Title: BACoN Cryostat Pressure Relief Calculations

Author(s):   Ramsey, John C.

Intended for: Report

Issued: 2013-10-31

BACoN Cryostat Pressure Relief Calculations

Ramsey 10/2013

Use this description: The BACoN cryostat is being constructed to determine the neutron energy spectrum of the LANSCE beam line at low rate (1 neutron per macropulse) in a liquid argon detector. It will utilize the scintillation light produced by nuclear recoils in argon to determine the energy via time of flight and provide data on the scintillation light yield for the CAPTAIN liquid argon TPC being designed and constructed now. The approximate volume of liquid argon contained within the cryostat is ~105 L.

The cryostat is a vacuum insulated design, with the liquid argon volume being surrounded entirely with insulating vacuum.

Volumes that could become pressurized must be appropriately relieved. The vacuum jacket will be relieved in accordance with CGA 341 6.4.2. This section states that the discharge area of the relief device shall be at least .34 mm^2/kg of water capacity of the liquid container. The water capacity of BACon is ~105L ~ 105 kg, thus the vacuum relief must be at least 35.7mm^2, or .055 in^2. The top flange of the vacuum jacket is held in place by vacuum pressure only, and in the event of a loss of vacuum, it will lift, relieving the system with substantially more available area than that required by CGA-341.

The relief of the liquid volume will be through one of the ports included in the vessel top head. A rupture disc will be mounted to a holder mounted to the conflat flange on the port. Behind the rupture disc will be a short pipe that routes relief effluent into the room.

This document details the calculations necessary to size that relief pipe for the BACoN commissioning location in the service building of the LSND tunnel (Bldg. 364) at the LANL LANSCE accelerator sight (TA-53).

Figure 1 shows a layout of the BACon cryostat.

The relief must transport the necessary effluent without over-pressurizing the cryostat vessel, the MAWP of which is assumed to be 15 psig. The outlet pressure for a fire condition must not exceed 121% MAWP (1.21 *(15+15) -15 = 21.3 psig) per UG-125 (2007 ASME Boiler and Pressure Vessel Code, 2008a Addenda, Section VIII, Division 1, 2008).

These calculations are based heavily on the work performed by Terry Tope at FermiLab, who has performed such calculations for a number of vessel installations there (Tope, 2008).
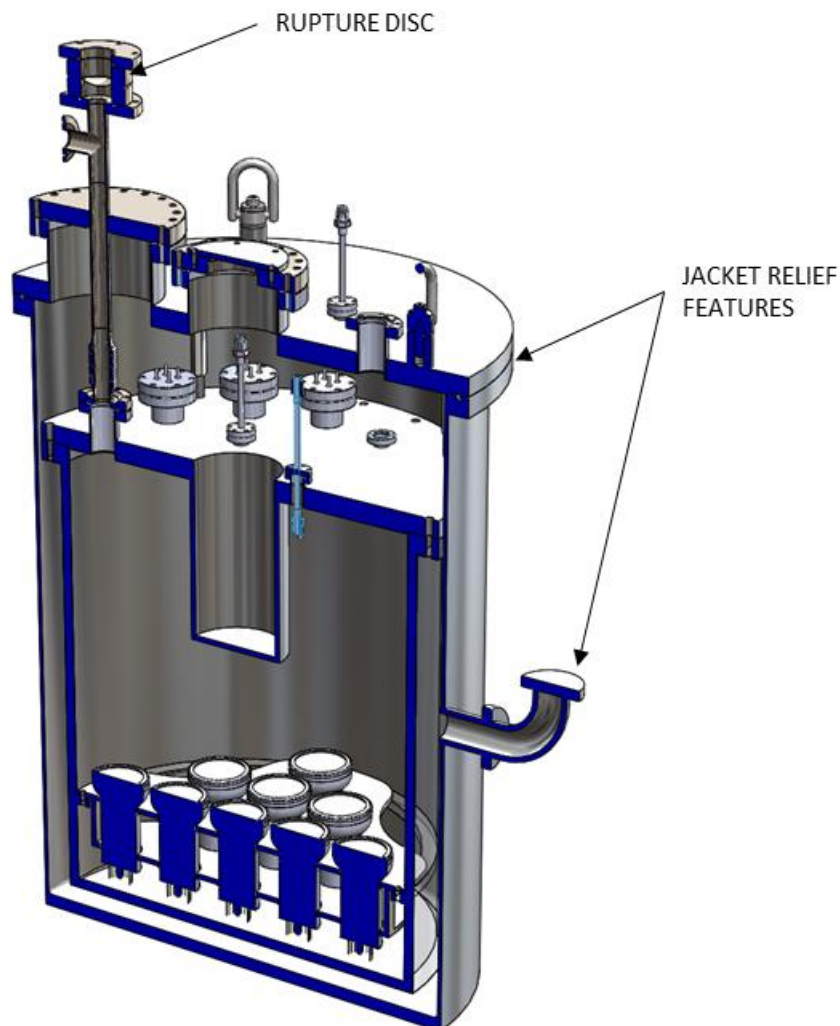
Figure 1. BACon Cryostat assembly.

It should be noted that a small relief will be included with the cryo feed system to account for any small pressure excursions during filling or operation, without necessarily rupturing the burst disc.

The relief system must be sized appropriately to relieve effluent from the cryostat from the worst reasonably conceivable failure mode. In this case, that is considered as a fire condition. This failure mode encompasses the mode where the vacuum space is spoiled, since the calculation includes heat transfer across the spoiled vacuum. In addition, a heat source (fire) is considered to surround the vessel.

To appropriately size the relief components, it is first necessary to understand the flow rate that it must transport. That flow rate is directly related to the heat flow into the liquid argon as a result of the failure scenario. In the most extreme case, the environment is considered to be fire at 922 K (Compressed Gas Association, 2008). Heat from the fire may enter the liquid argon through three independent paths. Path 1 passes through the vertical walls of the cryostat, including the spoiled vacuum space. Path 2 passes through the top head of the vacuum jacket, through the spoiled vacuum

space, and into the inner vessel. Path 3 passes through the bottom of the vacuum jacket, through the spoiled vacuum space, and into the inner vessel. The heat input via the three paths is calculated independently.

Calculation of heat input to the liquid argon in a fire scenario

Figure 2 shows a schematic of the fire scenario and relevant parameters.

TO ENVIRONMENT

RUPTURE DISC

FIRE
T1 = 922 K

$k_{air}, \alpha_{air}, \nu_{air}$

$A_{11} = 0.356\ m^2$
$\varepsilon_{11} = 0.5$
$T_{11} = ?$
PATH 2

$\varepsilon_{10} = 0.5$
$T_{10} = ?$

$A_9 = 0.338\ m^2$
$\varepsilon_9 = 0.5$
$T_9 = ?$

$A_2 = 1.435 m^2$
$\varepsilon_2 = 0.5$
$T_2 = ?$

k_{ss}

$A_8 = 0.257\ m^2$
$\varepsilon_8 = 0.1$
$T_8 = ?$

$\varepsilon_3 = 0.5$
$T_3 = ?$

$A_5 = 0.892\ m^2$
$\varepsilon_5 = 0.5$
$T_5 = ?$

LIQUID ARGON
$T_6 = 96.81$ K
$\varepsilon = 1.0$

$k_{air}, \alpha_{air}, \nu_{air}$

SPOILED VACUUM

PATH 1

$A_{13} = 0.271\ m^2$
$\varepsilon_{13} = 0.5$
$T_{13} = ?$

$\varepsilon_{14} = 0.5$
$T_{14} = ?$

$A_{15} = 0.203\ m^2$
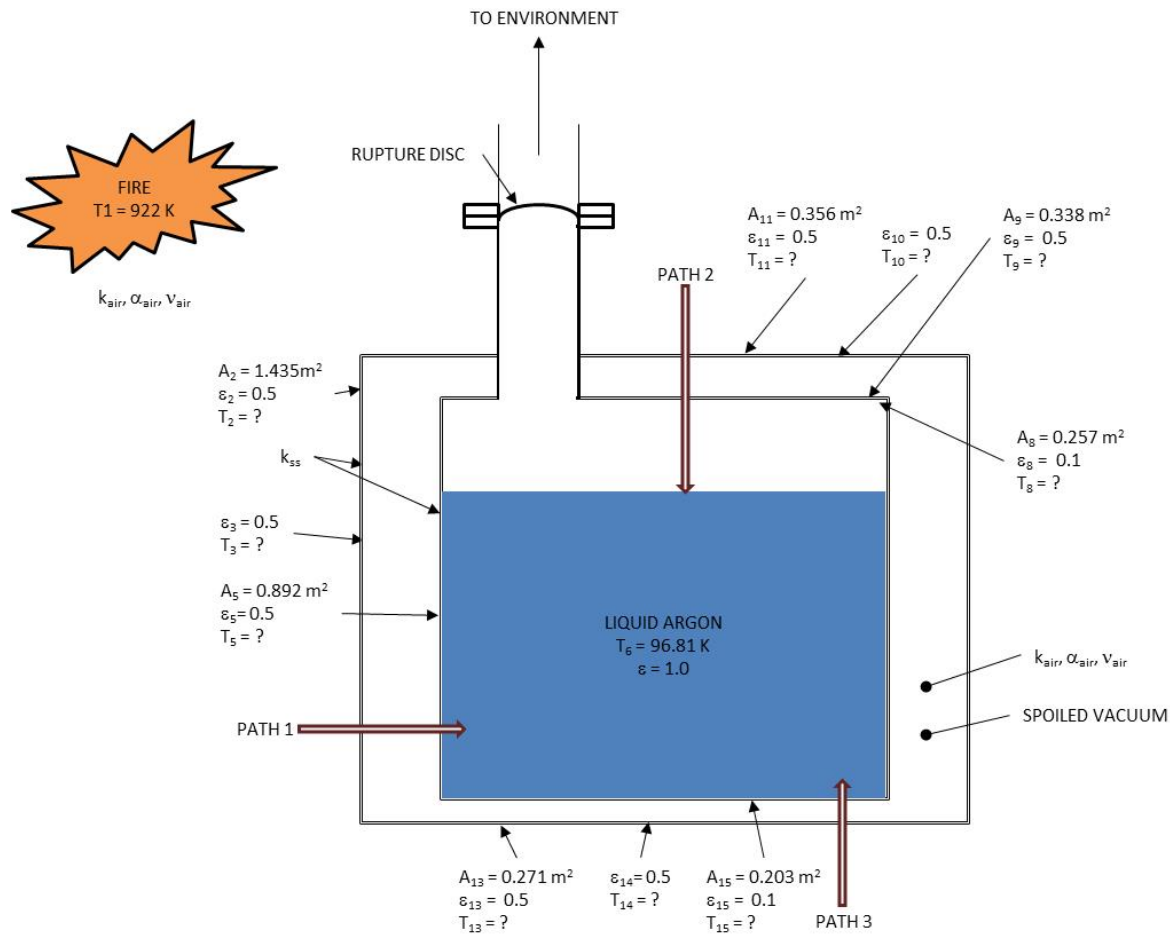$\varepsilon_{15} = 0.1$
$T_{15} = ?$
PATH 3

Figure 2. Schematic for fire pressure relief scenario

All calculations are performed by simultaneously solving the various heat transfer equations using the Engineering Equation Solver (EES) software package from F-Chart. This software is used because it contains the temperature dependent materials and fluid properties necessary to efficiently perform the necessary iterative calculations. The detailed of the EES calculation are provided in Appendix 1. Verification of the EES calculations is provided in Appendix 4.

The temperature of the liquid argon is assumed to be the saturation temperature at the relief pressure (21.3 psig) which is 96.81 K.

For the first path, heat transfers from the environment to the vertical portion of the cryostat cylindrical via radiation and convection, then through the vacuum jacket wall via conduction, then from the vacuum jacket shell to the inner vessel via radiation and convection, then through the inner vessel wall via conduction.

Radiation from the environment to the vertical sides of the vacuum jacket is predicted using Equation 13.27 from Incropera (Incropera, 1996).

$$q_{1-2rad} = \sigma A_2 \varepsilon_2 (T_1^4 - T_2^4)$$

Convection from the environment to the outer vessel vertical walls is modeled as flow over a vertical plate using Equation 9.26 from Incropera.

$$q_{1-2conv} = \left\{ 0.825 + \frac{0.387 Ra_L^{1/6}}{\left[\left(1 + 0.492/Pr \right)^{9/16} \right]^{8/27}} \right\}^2 \left(\frac{k_{air}}{L_{ext}} \right) A_2 (T_1 - T_2)$$

Convection heat transfer is generally analyzed using Nusselt correlations. The Nusselt number is defined as:

$$\overline{Nu}_L \equiv \frac{\bar{h}L}{k}$$

where h_{bar} is the overall convective heat transfer coefficient between the surface and the flowing gas, and k is thermal conductivity of the gas. For convection heat transfer analyses, all gas properties are evaluated at the film temperature [$(T_f = T_{surface} + T_\infty)/2$].

The Rayleigh number is also commonly used in such analyses, and it defined as:

$$Ra_L \equiv \frac{g\beta(T_{surface} - T_\infty)L^3}{\nu\alpha}$$

where g is the standard acceleration due to gravity, β is $1/T_f$, L is the characteristic length of the geometry, ν is the viscosity, and α is the thermal diffusivity of the gas.

Heat continuing along this path must next travel via conduction through the stainless steel wall of the vacuum jacket. Incropera Equation 3.27 provides a model for conduction across a cylindrical shell.

$$q_{2-3cond} = \frac{2\pi L_{ext} k (T_3 - T_2)}{\ln \frac{r_3}{r_2}}$$

Next, heat transfers between the inner surface of the vacuum jacket and the outer surface on the inner vessel through radiation and convection heat transfer. Incropera provides Equation 13.25 for radiation between two concentric cylinders.

$$q_{3-5rad} = \frac{-\sigma A_5 (T_3^4 - T_5^4)}{\frac{1}{\varepsilon_5} + \left(\frac{1-\varepsilon_3}{\varepsilon_3}\right)\left(\frac{r_3}{r_5}\right)}$$

Mills (Mills, 1999) provides a model for convection heat transfer between two concentric shells in Equation 4.101, where the largest of these three Nusselt numbers is to be used.

$$Nu_1 = 0.0605 Ra_L^{1/3} \qquad Nu_2 = \left\{ 1 + \left[\frac{0.104 Ra_L^{0.293}}{1 + \left(\frac{6310}{Ra_L}\right)^{1.36}} \right]^3 \right\}^{1/3} \qquad Nu_3 = 0.242 \left(\frac{Ra_L}{H/L}\right)^{0.272}$$

The largest of these Nusselt numbers is used in the standard convection heat transfer equation:

$$q_{3-5conv} = Nu_L \frac{k_{air}}{L} A_5 (T_5 - T_3)$$

Conduction through the inner vessel wall is similar to that of the outer vessel wall.

$$q_{5-6cond} = \frac{2\pi L_{ext}(T_6 - T_5)}{ln\frac{r_6}{r_5}}$$

These equations alone do not provide sufficient information to solve for temperatures and heat flows. We must also note that these various steps are in series, thus:

$$q_{2-3cond} = q_{1-2rad} + q_{1-2conv}$$

$$q_{5-6cond} = q_{3-5rad} + q_{3-5conv}$$

$$q_{2-3cond} = q_{5-6cond}$$

Supplying the known parameters and equations into EES yields the variable values shown in Appendix 2.

For the second path, heat transfers from the environment to the cryostat top lid via radiation and convection. The heat must then conduct across the thickness of the top head. Heat will then flow via radiation and convection from the vacuum jacket top head to the inner vessel top head. The heat will then conduct across the lid of the inner vessel. The gas will be flowing upward making heat transfer by conduction and convection through the gas negligible. Thus, radiation from the inner vessel lid into the liquid argon is dominant, but should be small, since the temperature difference should be very small.

Radiation to the top head may be approximated as a small convex surface in a large enclosure. Incropera Equation 13.27 models such geometry.

$$q_{1-11rad} = \sigma A_{11} \varepsilon_{11} (T_1^4 - T_{11}^4)$$

Convection from the environment to the top head is modeled as the top surface of a cooled plate, per Incropera Equation 9.32.

$$\overline{Nu_L} = 0.27 Ra_L{}^{1/4}$$

and

$$q_{1-11conv} = 0.27 Ra_L{}^{1/4} \frac{k_{air}}{L} A_{11}(T_1 - T_{11})$$

The heat then conducts through the top lid of the cryostat.

$$q_{11-10cond} = \frac{k_{SS} A_{10}(T_{11} - T_{10})}{L}$$

The heat then travels via radiation and convection between the inner surface of the vacuum jacket lid and the outer surface of the inner vessel lid. The radiation transfer is modeled as that between two parallel planes per Incropera Equation 13.24.

$$q_{10-9rad} = \frac{\sigma A_9 (T_{10}^4 - T_9^4)}{\dfrac{1}{\varepsilon_{10}} + \dfrac{1}{\varepsilon_9} - 1}$$

The convection is modeled as that within a rectangular cavity with the bottom cooled (τ=180°). Incropera section 9.8.1 notes that for this condition, heat transfer between the surfaces is purely by conduction, and the Nusselt number is 1, regardless of the Rayleigh number. To model this heat transport, the temperature of the gas is assumed to be the average temperature of the two surfaces, and the thermal conductivity is retrieved from EES lookup tables for that temperature.

$$q_{10-9cond} = \frac{k_{air} A_9 (T_{10} - T_9)}{L}$$

The heat then conducts through the inner vessel lid.

$$q_{9-8cond} = \frac{k_{ss} A_8 (T_9 - T_8)}{L}$$

Finally, the heat radiates to the liquid argon from the inner surface of the inner vessel lid. This radiation is modeled as that between two parallel planes per Incropera Equation 13.24.

$$q_{8-12rad} = \frac{\sigma A_{12} (T_8^4 - T_{12}^4)}{\dfrac{1}{\varepsilon_8} + \dfrac{1}{\varepsilon_{12}} - 1}$$

Gas evolution and flow out the top of the vessel will prevent effective convective and conductive heat transfer from the inner vessel lid to the liquid argon.

Again, we must note that the steps for this path are in series, thus:

$$q_{11-10cond} = q_{1-11rad} + q_{1-11conv}$$

$$q_{9-8cond} = q_{10-9rad} + q_{10-9cond}$$

$$q_{8-12rad} = q_{9-8cond}$$

$$q_{11-10cond} = q_{9-8cond}$$

For the third path, heat is transferred via convection and radiation to the vacuum jacket bottom surface from the environment. It is then conducted across the vacuum jacket wall. Convection and radiation then carry the heat from the inner surface of the vacuum jacket to the outer wall of the inner vessel. Finally, it is conducted across the inner vessel wall into the liquid argon. This is very similar to the model of the first path, except that the Nusselt correlations for this geometry are different.

$$q_{1-13rad} = \sigma A_{13} \varepsilon_{13}(T_1^4 - T_{13}^4)$$

Convection to the bottom surface of the cryostat is modeled as the bottom of a heated plate per Incropera Equation 9.32.

$$\overline{Nu}_L = 0.27 Ra_L^{1/4}$$

and

$$q_{1-13conv} = 0.27 Ra_L^{1/4} \frac{k_{air}}{L} A_{13}(T_1 - T_{13})$$

The heat then conducts through the bottom wall of the vacuum jacket.

$$q_{13-14cond} = \frac{k_{SS} A_{13}(T_{14} - T_{13})}{L}$$

Radiation between the inner surface of the vacuum jacket bottom head and the outer surface of the inner vessel bottom head is approximated at that between two parallel surfaces.

$$q_{14-15rad} = \frac{\sigma A_{15}(T_{14}^4 - T_{15}^4)}{\dfrac{1}{\varepsilon_{15}} + \dfrac{1}{\varepsilon_{14}} - 1}$$

Convection between the inner surface of the vacuum jacket bottom head and the outer surface of the inner vessel bottom head may be modeled as that in a horizontal cavity, approximated by Incropera Equation 9.49.

$$\overline{Nu}_L = 0.069 Ra_L^{1/3} Pr^{0.074}$$

and

$$q_{14-15conv} = 0.069 Ra_L{}^{1/3} Pr^{0.074} \frac{k_{air}}{L} A_{15}(T_{14} - T_{15})$$

Heat then conducts across the inner vessel wall into the liquid argon.

$$q_{15-16cond} = \frac{k_{SS} A_{15}(T_{15} - T_{16})}{L}$$

It should again be noted that the temperature liquid argon is assumed to be 96.81 K ($T_{16}=T_6$)

As in the previous paths, it must be noted that these heat transfer mechanisms are in parallel, and thus:

$$q_{13-14cond} = q_{1-13rad} + q_{1-13conv}$$

$$q_{15-16cond} = q_{14-15rad} + q_{14-15conv}$$

$$q_{15-16cond} = q_{13-14cond}$$

Appendix 1 shows the EES program used to simultaneously solve these equations, yielding temperatures at the various surfaces, as well as heat transfer rates for the various regions. The ultimate figure of importance is the output figure q_{total}, which is **9015 W**. This is the total calculated heat input from all three paths to the liquid argon in the event of fire.

Calculation of the pressure rise in the BACon cryostat as a result of fire scenario heat input

Assuming that all the heat calculated in the previous section (9015 W) is transferred into the liquid argon, and that the argon is at its saturation point, we can state that all of this heat goes into vaporizing the liquid argon.

The pipe sizing calculation may be done with a spreadsheet; however, for the sake of quick iteration with accurate materials and fluids properties, it is convenient to again turn to EES, and the calculation was included in the EES code shown in Appendix 1.

The energy required to vaporize liquid argon is the latent heat of vaporization, which is 160810 J/kg.

Dividing the total heat input by the latent heat of vaporization yields the mass flow rate of argon that the relief system must transport.

$$\dot{m} = \frac{q_{in}}{L_{vap}} \left[\frac{kg}{s}\right] = .056 \left[\frac{kg}{s}\right]$$

Dividing the mass flow rate by the gas density yields the volumetric flow rate. To determine the density of the gas, the gas temperature must be assumed. The gas as it evolves is very cold (just over the temperature of the liquid argon). For the purposes of this calculation, we assume that the gas warms instantaneously to 120K and remains at this temperature up to the vent exit.

$$\dot{V} = \frac{\dot{m}}{\rho_{gas}} \left[\frac{m^3}{s}\right] = \frac{.056 \left[\frac{kg}{s}\right]}{2.408 \left[\frac{kg}{m^3}\right]} = 0.023 \left[\frac{m^3}{s}\right]$$

Then the dimensions of the vent pipe may be introduced. By dividing the volumetric flow rate by the flow area of the pipe, we can get an average velocity of the gas. After a few iterations, a suitable ID of the vent pipe was determined to be .022 m (1" OD, .065" wall tube). The flow area for such a pipe is .00038 m².

$$V_{avg} = \frac{\dot{V}}{A_{flow}} \left[\frac{m}{s}\right] = \frac{.023 \left[\frac{m^3}{s}\right]}{.00038 \ [m^2]} = 60.53 \ [\frac{m}{s}]$$

We must then compare this velocity to the speed of sound in the gas, which is available through the EES software package. If the Mach number (the ratio of the average velocity to the velocity of the speed of sound in the gas) is less than 0.3, then the gas may be treated as incompressible for the calculation (Fox, 1992). Under the conditions described for this scenario, this criterion was met, and the calculations were performed for incompressible fluids.

9

Again, using the lookup functions of the EES software for gas properties, the Reynolds number is determined.

$$Re = \frac{\rho V d}{\mu} = 327549 \ (fully\ turbulent)$$

The Reynolds number, in combination with the relative roughness of the pipe (assumed to be .004 for these calculations) is used to look up the friction factor f using the Moody Chart. This functionality is available is a lookup function in EES, as well, which is .029.

Using these parameters, we may now calculate the loss factor (K factor) for the straight portions of the vent pipe per Crane (Flow of Fluids through Valves, Fittings, and Pipe, 1988). Assuming the length of the straight pipe is 0.5 m (venting into the room), we get:

$$K_{pipe} = \frac{f L_{pipe}}{D_{pipe}} = \frac{.029 * 0.5[m]}{.022[m]} = .657$$

The contribution of the straight pipe to the overall pressure drop is:

$$\Delta p = \frac{1}{2} K_{pipe} \rho V_{avg}{}^2 [Pa] = 2898\ [Pa] = .420\ [psi]$$

In addition to the loss factor from the pipe itself, there are also several other contributors to pressure drop in the vent system. These include the sudden constriction from the argon volume to the vent port (K=0.5), run flow through the pumping tee (K = 20f_t), the loss across the open rupture disc, and the vent's abrupt exit (K=1). With the exception of the rupture disc K factor, all of these numbers are available in Crane, and those numbers are used in the EES calculation.

The rupture disc is specified as a 1" nominal (DN 250) Oseco PRO+KRGL disc with an advertised loss coefficient of 0.69.

The maximum pressure allowed in the vessel is 21.3 psig, as described previously. The pressure at the outlet is assumed to be 0 psig. Under the calculated conditions, the pressure to drive the effluent out of the vessel through the venting system is *2.61* psi, which is substantially less than the 21.3 psig maximum.

Symbols

A	Surface area m^2
d	Pipe inner diameter (in)
f	Friction factor
h	Convection heat transfer coefficient (W/m^2-K)
H	Height (m)
k	Thermal conductivity (W/m-K)
L	Characteristic Length (m)
m	Mass (kg)
m_dot	Mass flow rate (kg/s)
n	Number of baffles
Nu_L	Nusselt Number
Pr	Prandtl Number
q	Heat transfer rate (W)
r	Radius (m)
Ra_L	Rayleigh Number
T	Temperature (K)
V	Velocity (m^3/s)
V_bar	Specific volume (m^3/kg)
V_dot	Volumetric flow rate (m^3/s)
α	Thermal diffusivity (m^2/s)
β	Volumetric thermal expansion coefficient (K^{-1})
ε	Emissivity
γ	Specific heat ratio
μ	Dynamic viscosity (Pa-s)
ν	Kinematic viscosity (m^2/s)
ρ	Density (kg/m^3)
σ	Stefan-Boltmann constant (5.670 x 10^{-8} W/m^2-K^4)

Works Cited

2007 ASME Boiler and Pressure Vessel Code, 2008a Addenda, Section VIII, Division 1. (2008). New York: The American Society of Mechanical Engineers.

Compressed Gas Association, I. (2008). *CGA S-1.3-2008.* Chantilly, VA: Compressed Gas Associations, Inc.

(1988). *Flow of Fluids through Valves, Fittings, and Pipe.* Crane Company Technical Paper No. 410M, Shenandoah, TX.

Fox, R. W. (1992). *Introduction to Fluid Mechanics, Fourth Edition.* New York: John Wiley and Sons.

Gilgen, R. R. (1994). Measurement and correlation of the (pressure, density, temperature) relation of argon II. *J. Chem. Thermodynamics*, 399-413.

Incropera, F. P. (1996). *Fundamentals of Heat and Mass Transfer, Fourth Edition.* New York: John Wiley and Sons.

Mills, A. (1999). *Heat Transfer, Second Edition.* Upper Saddle River, NJ: Prentice Hall.

Tope, T. (2008, September 17). *FLARE Materials Test Station and TPC Cryogenic Safety Report.* Retrieved from http://lartpc-docdb.fnal.gov/0002/000265/043/documentation_combined_1_6_09_small.pdf

Younglove, B. A. (1986). The Viscosity and Thermal Conductivity Coefficients of Gaseous and Liquid Argon. *J. Phys. Chem. Ref. Data*, 1323-1337.

Appendix 1 – EES heat input calculation details for CAPTAIN fire scenario

$TabStops 3 1 in

"This calculation is for an assumed fire condition (environmental temperature is 922K) for the BACon liquid argon cryostat. It is assumed that the cryostat is full of liquid argon, and that the vacuum is spoiled with air. It is also assumed that the multi-layer insulation is destroyed, providing no insulation value.

There are three heat input paths from the outside world into the liquid argon. Path 1 is through the vaccum jacket, assuming the vacuum is spoiled with air, and the insulation is destroyed, providing no insulating power. Path 2 is through the top plates into the argon. Path 3 is through the bottom plates into the argon."

"FUNCTIONS"

"K for gradual contraction"
Function K_Contract(d_large, d_small, angle_included)
beta = d_small/d_large

If(angle_included <= 45[deg]) Then
                K = (0.8 * sin(angle_included/2)*(1-beta^2))
Else
                K = (0.5 * sqrt(sin(angle_included/2)*(1-beta^2)))
EndIf
K_Contract = K
End

Function K_Expand(d_large, d_small, angle_included)
beta = d_small/d_large

If(angle_included <= 45[deg]) Then
                K = (2.6 * sin(angle_included/2)*(1-beta^2)^2)
Else
                K = (1-beta^2)^2
EndIf
K_Expand= K
End

"*CALCULATION INPUTS*"

T_1=922 [K]   "assumed temperature of the environment assuming fire conditions"
A_2=1.435 [m^2]   "outer vertical surface area of the vacuum jacket"
epsilon_2=0.5   "emissivity of vacuum jacket outer wall, dimensionless"
L_2=.775 [m]   "length of the vacuum jacket vertical sidewall"
epsilon_3=0.5   "emissivity of vacuum jacket inner wall, dimensionless"
epsilon_5=0.1   "emissivity of inner vessel outer wall, dimensionless"
A_5=.892 [m^2]   "outer surface area of the inner vessel"
T_6=96.81 [K]   "assumed temperature of the liquid argon, this is the saturation temperature at the 121%MAWP"

A_11=0.356 [m^2] "approximate area of the outer surface of the top head. rounded up"
epsilon_11=0.5   "emissivity of outside surface of top head"
D_11=0.64 [m]   "diameter of top head flange"
L_10=.025 [m]   "thickness of top head"
A_10=.389 [m^2]   "approximate area of the inner surface of the top head."
epsilon_10=0.5   "emissivity of the inside surface of the top head"

13

A_9=0.338 [m^2]   "approximate area of the top surface of the inner vessel lid"
epsilon_9=0.5   "emissivity of the top surface of the inner vessel lid"
L_10.9=.156 [m]   "distance between inner surface of the vacuum jacket and the outer surface of the
inner vessel lid"
A_8=0.257 [m^2]   "approximate area of the bottom surface of the inner vessel lid"
epsilon_8=0.5   "emissivity of the bottom surface of the inner vessel lid"
L_9.8=.025 [m]   "thickness of the inner vessel lid"

A_12=.183[m^2]   "approximate area of the liquid argon surface"
epsilon_12=1.0   "assumed emissivity of the liquid argon, or whatever interacts with incoming photons"
T_12=T_6   "assuming liquid argon is isothermal"

A_13=0.271 [m^2] "outer surface area of the vacuum jacket bottom head"
P_13=1.845 [m]   "perimiter of vacuum jacket bottom (where it meets the skirt)"
epsilon_13=0.5   "emissivity of the vacuum jacket bottom head"
A_15=.203 [m^2]   "outer surface area of the inner vessel bottom head"
epsilon_14=0.5   "emissivity of the inner surface of the vacuum jacket bottom head"
epsilon_15=0.1   "emissivity of the inner vessel bottom outer wall"
H_3.5=.559 [m]   "height of the annular space between the vacuum jacket and the inner vessel"
L_14.15=.022 [m]   "distance from inner surface of vacuum jacket bottom to outer surface of inner vessel
bottom"
L_14.13=.016 [m]   "thickness of the bottom head of the vacuum jacket"
L_15.16=.013 [m]   "thickness of the bottom head of the inner vessel"

r_2=.2935 [m]   "vessel wall radii"
r_3=.289 [m]
r_5=0.254 [m]
r_6=0.2415 [m]

q_system=15 [W]   "operating system heat load - from spreadsheet calculation - rounded up"

{Guess values for quality check}
{T_2=870 [K]   "guess at the temperature of the outer jacket for quality check"
T_3=867 [K]   "guess at the temperature of the inner wall of the vacuum jacket for quality check"
T_5=105 [K]   "guess at the temperature of the outer surface of the dewar wall for quality check"
T_11=870 [K]   "guess at the temperature of the outer surface of the top head for quality check"
T_10=867 [K]   "guess at the temperature of the inner wall of the top head for quality check"
T_13=870 [K]
T_14=867 [K]
T_15=105 [K]}

"*END HEAT CALCULATION INPUTS*"

"Path 1"

{1} q_1.2rad=sigma#*epsilon_2*A_2*(T_1^4-T_2^4)

beta_air1.2=1/((T_1+T_2)/2)
k_air1.2=Conductivity(Air_ha,T=((T_1+T_2)/2),P=Po#)
rho_air1.2=Density(Air_ha,T=((T_1+T_2)/2),P=Po#)
cp_air1.2=SpecHeat(Air_ha,T=((T_1+T_2)/2),P=Po#)
Pr_air1.2=Prandtl(Air_ha,T=((T_1+T_2)/2),P=Po#)
alpha_air1.2=k_air1.2/(rho_air1.2*cp_air1.2)*convert(W-m^2/kJ, m^2/s)
mu_air1.2=Viscosity(Air_ha,T=T_1,P=Po#)
nu_air1.2=mu_air1.2/rho_air1.2

qconvarg_1=g#*beta_air1.2*(T_1-T_2)*L_2^3/(alpha_air1.2*nu_air1.2)
{2} q_1.2conv=(0.825+((0.387*(qconvarg_1)^(1/6))/((1+(0.492/Pr_air1.2)^(9/16))^(8/27))))^2 *
(k_air1.2/L_2)*A_2*(T_1-T_2)   "convective load from the environment to the
outer surface of the jacket"

k_ss2.3=Conductivity(Stainless_AISI304, T=((T_3+T_2)/2))

{3} q_2.3cond=(2*pi#*L_2*k_ss2.3*(T_3-T_2))/(ln(r_3/r_2))

{4} q_3.5rad=(sigma#*A_5*(T_3^4-T_5^4))/((1/epsilon_5)+((1-epsilon_3)/epsilon_3)*(r_5/r_3))

beta_air3.5=1/((T_3+T_5)/2)
k_air3.5=Conductivity(Air_ha,T=((T_3+T_5)/2), P=Po#)
rho_air3.5=Density(Air_ha,T=((T_3+T_5)/2), P=Po#)
cp_air3.5=SpecHeat(Air_ha,T=((T_3+T_5)/2), P=Po#)
Pr_air3.5=Prandtl(Air, T=((T_3+T_5)/2))
alpha_air3.5=k_air3.5/(rho_air3.5*cp_air3.5)*convert(W-m^2/kJ, m^2/s)
mu_air3.5=Viscosity(Air_ha, T=((T_3+T_5)/2), P=Po#)
nu_air3.5=mu_air3.5/rho_air3.5
L_annular3.5=r_3-r_5

Ra_L3.5=(g#*beta_air3.5*(T_3-T_5))*L_annular3.5^3/(nu_air3.5*alpha_air3.5)

"Per Mills, use the largest Nu number of these three to calculate convection in an annular space:"

Nusselt_35[1]=.0605*Ra_L3.5^(1/3)
Nusselt_35[2]=((1+((.104*Ra_L3.5^.293)/(1+(6310/Ra_L3.5)^1.36))^3))^(1/3)
Nusselt_35[3]=0.242*(Ra_L3.5/(H_3.5/L_annular3.5))^.272

Nusselt_3.5max1 = MAX(Nusselt_35[1], Nusselt_35[2])
Nusselt_3.5max = MAX(Nusselt_3.5max1, Nusselt_35[3])

{5} q_3.5conv=Nusselt_3.5max*(k_air3.5/L_annular3.5)*A_5*(T_3-T_5)

k_ss5.6=Conductivity(Stainless_AISI304, T=((T_5+T_6)/2))

{6} q_5.6cond=(2*pi#*L_2*k_ss5.6*(T_6-T_5))/(ln(r_6/r_5))

"Additional relations"
q_2.3cond=q_1.2rad+q_1.2conv
q_5.6cond=q_3.5rad+q_3.5conv
q_5.6cond=q_2.3cond

"Path 2"

{1}
q_1.11rad=sigma#*A_11*epsilon_11*(T_1^4-T_11^4)

beta_air1.11=1/((T_1+T_11)/2)
L_top=A_11/(pi#*D_11)
k_air1.11=Conductivity(Air_ha,T=((T_1+T_11)/2),P=Po#)
rho_air1.11=Density(Air_ha,T=((T_1+T_11)/2),P=Po#)
cp_air1.11=SpecHeat(Air_ha,T=((T_1+T_11)/2),P=Po#)

Pr_air1.11=Prandtl(Air,T=((T_1+T_11)/2))
alpha_air1.11=k_air1.11/(rho_air1.11*cp_air1.11)*convert(W-m^2/kJ, m^2/s)
mu_air1.11=Viscosity(Air_ha,T=((T_1+T_11)/2),P=Po#)
nu_air1.11=mu_air1.11/rho_air1.11
Ra_L1.11=g#*beta_air1.11*(T_1-T_11)*L_top^3/(alpha_air1.11*nu_air1.11)

{2}
q_1.11conv=0.27*Ra_L1.11^(1/4)*(k_air1.11/L_top)*A_11*(T_1-T_11)

k_ss11.10=Conductivity(Stainless_AISI304, T=((T_11+T_10)/2))

{3}
q_11.10cond=k_ss11.10*A_10*(T_11-T_10)/L_10

{4}
q_10.9rad=A_9*sigma#*(T_10^4-T_9^4)/((1/epsilon_10)+(1/epsilon_9)-1)

k_air10.9=Conductivity(Air_ha,T=((T_10+T_9)/2),P=Po#)

{5}
q_10.9cond=k_air10.9*A_9*(T_10-T_9)/L_10.9

k_ss9.8=Conductivity(Stainless_AISI304, T=((T_9+T_8)/2))

{6}
q_9.8cond=k_ss9.8*A_8*(T_9-T_8)/L_9.8

{7}
q_8.12rad=sigma#*A_12*(T_8^4-T_6^4)/((1/epsilon_8)+(1/epsilon_12)-1)

"Additional relations"
{T_12=T_6}
q_11.10cond=q_1.11rad+q_1.11conv
q_9.8cond=q_10.9rad+q_10.9cond
q_8.12rad=q_9.8cond
q_9.8cond=q_11.10cond

"Path 3"

{1}
q_1.13rad=sigma#*epsilon_13*A_13*(T_1^4-T_13^4)

beta_air1.13=1/((T_1+T_13)/2)
k_air1.13=Conductivity(Air_ha,T=((T_1+T_13)/2),P=Po#)
rho_air1.13=Density(Air_ha,T=((T_1+T_13)/2),P=Po#)
cp_air1.13=SpecHeat(Air_ha,T=((T_1+T_13)/2),P=Po#)
Pr_air1.13=Prandtl(Air,T=((T_1+T_13)/2))
alpha_air1.13=k_air1.13/(rho_air1.13*cp_air1.13)*convert(W-m^2/kJ, m^2/s)
mu_air1.13=Viscosity(Air_ha,T=((T_1+T_14)/2),P=Po#)
nu_air1.13=mu_air1.13/rho_air1.13
Ra_L1.13=g#*beta_air1.13*(T_1-T_13)*(A_13/P_13)^3/(alpha_air1.13*nu_air1.13)

{2}
q_1.13conv=0.27*Ra_L1.13^(.25)* k_air1.13/(A_13/P_13)*A_13*(T_1-T_13)

k_ss13.14=Conductivity(Stainless_AISI304, T=((T_13+T_14)/2))

{3}
q_13.14cond=k_ss13.14*A_13*(T_14-T_13)/(L_14.13)

{4}
q_14.15rad=(sigma#*A_15*(T_14^4-T_15^4))/((1/epsilon_15)+(1/epsilon_14)-1)

beta_air14.15=1/((T_14+T_15)/2)
k_air14.15=Conductivity(Air_ha,T=((T_14+T_15)/2), P=Po#)
rho_air14.15=Density(Air_ha,T=((T_14+T_15)/2), P=Po#)
cp_air14.15=SpecHeat(Air_ha,T=((T_14+T_14)/2), P=Po#)
Pr_air14.15=Prandtl(Air, T=((T_14+T_15)/2))
alpha_air14.15=k_air14.15/(rho_air14.15*cp_air14.15)*convert(W-m^2/kJ, m^2/s)
mu_air14.15=Viscosity(Air_ha, T=((T_14+T_15)/2), P=Po#)
nu_air14.15=mu_air14.15/rho_air14.15

Ra_L14.15=(g#*beta_air14.15*(T_14-T_15))*L_14.15^3/(nu_air14.15*alpha_air14.15)
Nusselt_14.15=.069*Ra_L14.15^(1/3)*Pr_air14.15^(.074)

{5}
q_14.15conv=Nusselt_14.15*(k_air14.15/L_14.15)*A_15*(T_14-T_15)

k_ss15.16=Conductivity(Stainless_AISI304, T=((T_15+T_16)/2))

{6}
q_15.16cond=k_ss15.16*A_15*(T_15-T_16)/(L_15.16)

"Additional relations"
T_16=T_6
q_13.14cond=q_1.13rad+q_1.13conv
q_15.16cond=q_14.15rad+q_14.15conv
q_15.16cond=q_13.14cond

"Total heat input from all paths"
q_total=q_5.6cond+q_8.12rad+q_15.16cond+q_system

"For fire, the pressure must not exceed 121% MAWP. In this case, the MAWP is 15 psig, so
1.21*(15+15)-15=21.3 psig."
"The heating rate to the liquid argon is calculated above"

L_HV = 160810 [J/kg]
d_pipe = 0.022098 [m]
L_straight = 0.5 [m]
T_gas = 120 [K]   "Assumed gas temperature, assume it becomes
warm before leaving cryostat"
P_gas = ((DeltaP_Total+14.7[psi]) * convert(psia, Pa))/2
RR_pipe = .004   "Assumed pipe relative roughness"
{k = 1.67}
Z_gas=CompressibilityFactor(Argon,T=T_gas,P=P_gas)
F_relief = 1.0   "connection to rupture disc is < 2' per CGA
6.1.4"

"*END USER INPUT*"

"Flow through straight pipe length"

m_dot = q_total / L_HV
rho_gas=Density(Argon,T=T_gas,P=P_gas)
V_dot = m_dot / rho_gas
SS_gas = SoundSpeed(Argon,T=T_gas,P=P_gas)
A_flow = pi# * d_pipe^2/4
V_avg = V_dot / A_flow
Mach_gas = V_avg / SS_gas
mu_gas = Viscosity(Argon, T=T_gas, P=P_gas)
Re_gas = rho_gas * V_avg * d_pipe / mu_gas
f={.014} MoodyChart(Re_gas, RR_pipe)
K_straight = f * L_straight / d_pipe
DeltaP[0]= (0.5 * K_straight * rho_gas * V_avg^2) * convert(Pa, psi)
M_argon = 39.948 [g/mol]

"Additional K factors and resulting DeltaP"

"K_1"
K_1 = 0.5   "Sudden constriction to vent pipe - (Crane, 1999)"
n_K1 = 1   "Number of K_1 features"
DeltaP[1] = n_K1 * 0.5 * K_1 * rho_gas * V_avg^2 * convert(Pa, psi)

"K_2"
K_2 = 20 * f   "Run flow through tee (Crane, 1999)"
n_K2 = 1   "Number of K_2 features"
DeltaP[2] = n_K2 * 0.5 * K_2 * rho_gas * V_avg^2 * convert(Pa, psi)

"K_3"
K_3 = 0.69   "Rupture disc - Oseco"
n_K3 = 1   "Number of K_3 features"
DeltaP[3] = n_K3 * 0.5 * K_3 * rho_gas * V_avg^2 * convert(Pa, psi)

"K_4"
K_4=K_Sudden_Expansion(.022 [m],.051 [m])
n_K4 = 1   "Number of K_4 features"
DeltaP[4] = n_K4 * 0.5 * K_4 * rho_gas * V_avg^2 * convert(Pa, psi)

"K_5"
K_5 = 1   "Abrupt exit (Crane, 1999)"
n_K5 = 1   "Number of K_5 features"
DeltaP[5] = n_K5 * 0.5 * K_5 * rho_gas * V_avg^2 * convert(Pa, psi)

DeltaP_Total = SUM(DeltaP[i], i = 0,5)

"Check calculated pressure drop vs. Compressible Darcy (Crane Equation 1-11)"
K_tot=K_straight+k_1*n_K1+K_2*n_K2+K_3*n_K3+K_4*n_K4+K_5*n_K5

dPsonic_P1=.1107*ln(K_tot)+0.5312

Y_sonic=.0434*ln(K_tot)+0.5889
Y_actual=1-((1-Y_sonic)/(dPsonic_P1))*(DeltaP_TotalDarcypsi/(DeltaP_TotalDarcypsi+14.7[psi]))

d_pipemm=d_pipe*convert(m, mm)
V_bargas=.534 [m^3/kg]
m_dot = .000001111*Y_actual*d_pipemm^2*sqrt(DeltaP_TotalDarcy/K_tot/V_bargas)
DeltaP_TotalDarcypsi=DeltaP_TotalDarcy*convert(Pa, psi)
dP_PPrime = DeltaP_TotalDarcypsi/(21.3[psi]+14.7[psi])

Unit Settings: SI K Pa kJ mass deg

$\alpha_{air1.11} = 0.0001412$ [m²/s]	$\alpha_{air1.13} = 0.00014$ [m²/s]	$\alpha_{air1.2} = 0.0001416$ [m²/s]	$\alpha_{air14.15} = 0.00004809$ [m²/s]
$\alpha_{air3.5} = 0.00005268$ [m²/s]	$A_{10} = 0.389$ [m²]	$A_{11} = 0.356$ [m²]	$A_{12} = 0.183$ [m²]
$A_{13} = 0.271$ [m²]	$A_{15} = 0.203$ [m²]	$A_2 = 1.435$ [m²]	$A_5 = 0.892$ [m²]
$A_8 = 0.257$ [m²]	$A_9 = 0.338$ [m²]	$A_{flow} = 0.0003835$ [m²]	$\beta_{air1.11} = 0.001117$ [1/K]
$\beta_{air1.13} = 0.001123$ [1/K]	$\beta_{air1.2} = 0.001114$ [1/K]	$\beta_{air14.15} = 0.002064$ [1/K]	$\beta_{air3.5} = 0.00205$ [1/K]
$cp_{air1.11} = 1.12$ [kJ/kg-K]	$cp_{air1.13} = 1.119$ [kJ/kg-K]	$cp_{air1.2} = 1.121$ [kJ/kg-K]	$cp_{air14.15} = 1.113$ [kJ/kg-K]
$cp_{air3.5} = 1.028$ [kJ/kg-K]	$\delta P_{Total} = 2.625$ [psi]	$\delta P_{TotalDarcy} = 29773$ [Pa]	$\delta P_{TotalDarcypsi} = 4.318$ [psi]
$dPsonic_{P1} = 0.6869$	$dP_{PPrime} = 0.12$	$D_{11} = 0.64$ [m]	$d_{pipe} = 0.0221$ [m]
$d_{pipemm} = 22.1$ [mm]	$\varepsilon_{10} = 0.5$	$\varepsilon_{11} = 0.5$	$\varepsilon_{12} = 1$
$\varepsilon_{13} = 0.5$	$\varepsilon_{14} = 0.5$	$\varepsilon_{15} = 0.1$	$\varepsilon_2 = 0.5$
$\varepsilon_3 = 0.5$	$\varepsilon_5 = 0.1$	$\varepsilon_8 = 0.5$	$\varepsilon_9 = 0.5$
$f = 0.02888$	$F_{relief} = 1$	$H_{3.5} = 0.559$ [m]	$K_1 = 0.5$
$K_2 = 0.5775$	$K_3 = 0.69$	$K_4 = 0.6625$	$K_5 = 1$
$k_{air1.11} = 0.06231$ [W/m-K]	$k_{air1.13} = 0.06205$ [W/m-K]	$k_{air1.2} = 0.0624$ [W/m-K]	$k_{air10.9} = 0.05763$ [W/m-K]
$k_{air14.15} = 0.03897$ [W/m-K]	$k_{air3.5} = 0.03917$ [W/m-K]	$k_{ss11.10} = 23.54$ [W/m-K]	$k_{ss13.14} = 23.45$ [W/m-K]
$k_{ss15.16} = 9.257$ [W/m-K]	$k_{ss2.3} = 23.61$ [W/m-K]	$k_{ss5.6} = 9.207$ [W/m-K]	$k_{ss9.8} = 21.84$ [W/m-K]
$K_{straight} = 0.6534$	$K_{tot} = 4.083$	$L_{10} = 0.025$ [m]	$L_{10.9} = 0.156$ [m]
$L_{14.13} = 0.016$ [m]	$L_{14.15} = 0.022$ [m]	$L_{15.16} = 0.013$ [m]	$L_2 = 0.775$ [m]
$L_{9.8} = 0.025$ [m]	$L_{annular3.5} = 0.035$ [m]	$L_{HV} = 160810$ [J/kg]	$L_{straight} = 0.5$ [m]
$L_{top} = 0.1771$ [m]	$Mach_{gas} = 0.2983$	$\mu_{air1.11} = 0.00004026$ [kg/m-s]	$\mu_{air1.13} = 0.00004017$ [kg/m-s]
$\mu_{air1.2} = 0.00004104$ [kg/m-s]	$\mu_{air14.15} = 0.00002649$ [kg/m-s]	$\mu_{air3.5} = 0.00002661$ [kg/m-s]	$\mu_{gas} = 0.000009861$ [kg/m-s]
$M_{argon} = 39.95$ [g/mol]	$\dot{m} = 0.05606$ [kg/s]	$Nusselt_{14.15} = 3.045$	$Nusselt_{3.5max} = 4.348$
$Nusselt_{3.5max1} = 4.348$	$\nu_{air1.11} = 0.0001022$ [m²/s]	$\nu_{air1.13} = 0.0001014$ [m²/s]	$\nu_{air1.2} = 0.0001044$ [m²/s]
$\nu_{air14.15} = 0.00003639$ [m²/s]	$\nu_{air3.5} = 0.00003679$ [m²/s]	$n_{K1} = 1$	$n_{K2} = 1$
$n_{K3} = 1$	$n_{K4} = 1$	$n_{K5} = 1$	$Pr_{air1.11} = 0.705$
$Pr_{air1.13} = 0.7047$	$Pr_{air1.2} = 0.724$	$Pr_{air14.15} = 0.6977$	$Pr_{air3.5} = 0.6974$
$P_{13} = 1.845$ [m]	$P_{gas} = 59725$ [Pa]	$qconvarg_1 = 1.700E+07$	$q_{1.11conv} = 38.88$ [W]
$q_{1.11rad} = 1535$ [W]	$q_{1.13conv} = 38.62$ [W]	$q_{1.13rad} = 1368$ [W]	$q_{1.2conv} = 207.8$ [W]
$q_{1.2rad} = 5811$ [W]	$q_{10.9cond} = 14.43$ [W]	$q_{10.9rad} = 1560$ [W]	$q_{11.10cond} = 1574$ [W]
$q_{13.14cond} = 1407$ [W]	$q_{14.15conv} = 827.9$ [W]	$q_{14.15rad} = 579.1$ [W]	$q_{15.16cond} = 1407$ [W]
$q_{2.3cond} = 6019$ [W]	$q_{3.5conv} = 3334$ [W]	$q_{3.5rad} = 2685$ [W]	$q_{5.6cond} = 6019$ [W]
$q_{8.12rad} = 1574$ [W]	$q_{9.8cond} = 1574$ [W]	$q_{system} = 15$ [W]	$q_{total} = 9015$ [W]
$Ra_{L1.11} = 222814$	$Ra_{L1.13} = 154877$	$Ra_{L14.15} = 93098$	$Ra_{L3.5} = 341680$
$Re_{gas} = 327549$	$\rho_{air1.11} = 0.3939$ [kg/m³]	$\rho_{air1.13} = 0.3961$ [kg/m³]	$\rho_{air1.2} = 0.3931$ [kg/m³]
$\rho_{air14.15} = 0.728$ [kg/m³]	$\rho_{air3.5} = 0.7233$ [kg/m³]	$\rho_{gas} = 2.411$ [kg/m³]	$RR_{pipe} = 0.004$
$r_2 = 0.2935$ [m]	$r_3 = 0.289$ [m]	$r_5 = 0.254$ [m]	$r_6 = 0.2415$ [m]
$SS_{gas} = 203.3$ [m/s]	$T_1 = 922$ [K]	$T_{10} = 864.8$ [K]	$T_{11} = 869.1$ [K]
$T_{12} = 96.81$ [K]	$T_{13} = 859$ [K]	$T_{14} = 862.6$ [K]	$T_{15} = 106.5$ [K]
$T_{16} = 96.81$ [K]	$T_2 = 872.6$ [K]	$T_3 = 871.8$ [K]	$T_5 = 103.6$ [K]
$T_6 = 96.81$ [K]	$T_8 = 742.2$ [K]	$T_9 = 749.3$ [K]	$T_{gas} = 120$ [K]
$V_{avg} = 60.64$ [m/s]	$V_{bargas} = 0.534$ [m³/kg]	$\dot{V} = 0.02326$ [m³/s]	$Y_{actual} = 0.8843$
$Y_{sonic} = 0.65$	$Z_{gas} = 0.992$		

Appendix 3 – OSECO Burst Disc Capacity at the Desired Pressure

OSECO pressure intelligence

1701 W. Tacoma
Broken Arrow
Oklahoma 74012
USA

Tel: 918-258-5626
Fax: 918-251-2809
Email: info@oseco.com

Gas / Vapor Capacity

10/9/2013

Prepared For:	LANL
cc:	
OSECO Reorder Number:	
Tag Number:	
Project Number:	
Burst Pressure:	15 psi(g)
Back Pressure:	0 psi(g)
Over Pressure:	10 %
Burst Temperature:	72 F
Flow Media:	Argon
Molecular Weight:	39.948
Ratio of Specific Heats:	1.667
Compressibility Factor:	1
Flow Area:	in^2
Barametric Pressure:	14.7 psi(g)
Discharge Coefficient:	0.62
Disc Type:	PRO + KRGL
Disc Size:	1.5 in

Flow is Sonic

Disc Capacity kg/hr

1,849.25

Sizing equations are based on the rupture disks venting directly to atmosphere, being installed within eight pipe diameters form the vessel nozzle entry, and with a discharge pipe no longer than five pip diameters.

TÜV CERT
ISO 9001

OSECO / 1701 West Tacoma / Broken Arrow, Oklahoma 74012
Telephone 800-395-3475 / Fax 800-396-2809 / www.oseco.com
Quality Products to Meet Industy Needs!

A HALMA GROUP COMPANY

Sizing equations are based on the rupture disks venting directly to atmosphere, being installed within eight pipe diameters form the vessel nozzle entry, and with a discharge pipe no longer than five pip diameters.

Appendix 4 – Verification of EES Calculations

To ensure the quality and accuracy of the program used to perform the calculation above, it is useful to duplicate the calculation using alternative methods and check for agreement. The EES software was necessary to perform the iterative calculation to find the temperatures at the various points in the apparatus. For this verification, we take the temperature numbers supplied by EES, plug them back into the heat transfer equations, and make sure that the output agrees within reason. We will also obtain thermodynamic data from alternative (non-EES) sources for the various materials and fluids at the relevant temperatures to confirm the quality of these properties.

Fire scenario heat input verification

To verify the calculation, we will work through the equations presented above, starting with the heat input to the outer shell via radiation heat transfer:

$$q_{1-2rad} = \sigma A_2 \varepsilon_2 (T_1^4 - T_2^4)$$

From the CAD model, we have A_2 = 1.435 m^2. We assume that the emissivity of the stainless steel is 0.5. The temperature of the environment (T_1) is 922 K from the problem definition. So:

$$q_{1-2rad} = \sigma(1.435\ m^2)(0.5)((922\ K)^4 - (872.6K)^4) = 5812\ W$$

This agrees with the output from the EES program.

Next we look at convection heat transfer from the environment to the outer vessel vertical walls, modeled as flow over a vertical plate using Equation 9.26 from Incropera.

$$q_{1-2conv} = \left\{ 0.825 + \frac{0.387 Ra_L^{1/6}}{\left[\left(1 + 0.492/Pr\right)^{9/16} \right]^{8/27}} \right\}^2 \left(\frac{k_{air}}{L_{ext}}\right) A_2(T_1 - T_2)$$

It must also be noted that:

$$\overline{Nu}_L = \frac{\bar{h}L}{k}$$

and:

$$Ra_L = \frac{g\beta(T_\infty - T_s)L^3}{\nu\alpha}$$

So to verify this, we must first calculate the Rayleigh number. All properties are evaluated at the "film temperature" (T_f) which is (T_s + T_∞) / 2 = (872.6 K + 922 K) / 2 = 897.3 K. $\beta = T_f^{-1}$ = .0011. From the CAD model, the characteristic length L (the height of the vacuum jacket sidewall) is 0.775m. At atmospheric pressure and the film temperature, the viscosity of air is 102.4 x 10^{-6} m^2/s, and the thermal diffusivity is 142.4 x 10^{-6} m^2/s. These numbers are interpolated from Table A-4 in Incropera.

Plugging in these values yields a Rayleigh Number of 1.70 x 10^7.

To confirm the convective heat transfer calculation, we must also have the Prandtl number and the thermal conductivity of the air. From Incropera Table A-4 at the film temperature and atmospheric pressure, Pr is .718, and k is 60.68 x 10^{-3} W/m-K). So:

$$q_{1-2conv} = \left\{0.825 + \frac{0.387(1.7 \times 10^7)^{1/6}}{\left[\left(1 + {0.492}/{0.718}\right)^{9/16}\right]^{8/27}}\right\}^2 \left(\frac{.0607}{.775}\right)(1.435)(922 - 872.6) = 236\,W$$

The result from EES is 207.2 W. This difference is the result of minor differences between the thermal conductivity of the air sourced from EES vs. that from Incropera.

As stated previously, heat continuing along this path must next travel via conduction through the stainless steel wall of the vacuum jacket. Incropera Equation 3.27 provides a model for conduction across a cylindrical shell.

$$q_{2-3cond} = \frac{2\pi L_{ext}k(T_3 - T_2)}{ln\frac{r_3}{r_2}}$$

From the CAD model, r_2 = .2935 and r_3 = .289m. From the calculation, T_3 = 871.8 K. The thermal conductivity (k) of stainless steel should be evaluated at the average wall temperature, which is 872.2 K. I don't have a resource to get the number at the exact temperature, but I do have the number at 773 K from Matweb.com, which is 21.5 W/m-K, which is comparable to the EES value of 23.61 W/m-K. Plugging these values into the equation:

$$q_{2-3cond} = \frac{2\pi(0.775)(21.5)(871.8 - 872.6)}{ln\frac{.289}{.2935}} = 5421\,W$$

This is in fair agreement with the 6019 W output from EES. Plugging in the 23.61 W/m-K value for k from EES brings the number to 5953 W, which is in close agreement with EES, with the difference being due to rounding errors.

As described earlier, heat then transfers between the inner surface of the vacuum jacket and the outer surface on the inner vessel through radiation and convection heat transfer. Incropera provides Equation 13.25 for radiation between two concentric cylinders.

$$q_{3-5rad} = \frac{-\sigma A_5(T_3^4 - T_5^4)}{\frac{1}{\varepsilon_5} + \left(\frac{1 - \varepsilon_3}{\varepsilon_3}\right)\left(\frac{r_5}{r_3}\right)}$$

From the EES calculation, T_5 is 103.6 K. The emissivity of surface 3 is assumed to be 0.5, and the emissivity of surface 5 is assumed to be 0.1, since it is quite a bit cooler. From the CAD model, A_5 is .892 m^2, and r_5 = .254 m. Plugging these values into the equations yields:

$$q_{3-5rad} = \frac{-\sigma(.892)(871.8^4 - 103.6^4)}{\frac{1}{.1} + \left(\frac{1-.5}{.5}\right)\left(\frac{.254}{.289}\right)} = 2685\ W$$

This agrees with the 2685 W result from EES.

We must next evaluate the convection calculation between the inner surface of the vacuum jacket and the outer surface of the liquid argon volume.

As stated previously, Mills (Mills, 1999) provides a model for convection heat transfer between two concentric shells in Equation 4.101, where the largest of these three Nusselt numbers is to be used.

$$Nu_1 = 0.0605 Ra_L{}^{1/3} \qquad Nu_2 = \left\{1 + \left[\frac{0.104 Ra_L{}^{0.293}}{1 + \left(\frac{6310}{Ra_L}\right)^{1.36}}\right]^3\right\}^{1/3} \qquad Nu_3 = 0.242\left(\frac{Ra_L}{H/_L}\right)^{0.272}$$

We must determine which of these 3 Nusselt numbers is the largest.

$$Ra_L = \frac{g\beta(T_3 - T_5)L^3}{\nu\alpha}$$

In this case, $\beta = 1/((T_3+T_5)/2) = .0021$. From the CAD model, the characteristic length L is .035 m and H = .559 m. At the average temperature (487.7 K), per Incropera Table A-4, the viscosity is 37.21 x 10^{-6} m^2/s, the thermal diffusivity is 54.36 x 10^{-6} m^2/s, and the thermal conductivity is .0399 W/m-K. Plugging these numbers into the equation yields a Rayleigh number of 3.35 x 10^5, which agrees well with the 3.41 x 10^5 number from the EES calculation.

Using this value of the Rayleigh number, Nu_1 = 4.23, Nu_2 = 4.32, Nu_3 = 3.625. These are in excellent agreement from the values from EES.

The largest of these Nusselt numbers (Nu_2) is used in the standard convection heat transfer equation:

$$q_{3-5conv} = Nu_L\frac{k_{air}}{L}A_5(T_3 - T_5) = 4.32\left(\frac{.0399}{.035}\right)(.892)(871.8 - 103.6) = 3375\ W$$

This agrees well with the EES output of 3334 W.

Next, we evaluate the conduction through the inner vessel wall.

$$q_{5-6cond} = \frac{2\pi L_{ext}k(T_6 - T_5)}{ln\frac{r_6}{r_5}}$$

From the CAD model, L = .775, r_5 = .254 m, and r_6 = .2415 m. T_6 is assumed to be the saturation temperature at the pressure in the argon volume. Per interpolation from (Gilgen, 1994) Table 1, this is 96.58 K at 21.3 psig (.248 MPa), which is in very close agreement with the value 96.81 K from EES. Per

NIST, the thermal conductivity (k) of 304 stainless steel at 100K is 9.223 W/m²-K. Plugging these values into the equation yields a heat flow of 6043 W, which is in good agreement with the EES output of 6019 W.

These equations alone do not provide sufficient information to solve for temperatures and heat flows. We must also note that these various steps are in series, thus:

$$q_{2-3cond} = q_{1-2rad} + q_{1-2conv}$$

$$q_{5-6cond} = q_{3-5rad} + q_{3-5conv}$$

$$q_{2-3cond} = q_{5-6cond}$$

The values calculated above should also satisfy these equations within reason:

$$5953\ W \approx 5812\ W + 236\ W = 6048\ W$$

$$6019\ W \approx 2685\ W + 3375\ W = 6060\ W$$

$$5953\ W \approx 6019\ W$$

All of these values for the heat balance agree within reason.

As for the first path, we can verify the calculations by marching through the process by hand and checking the thermodynamic properties provided by EES.

Radiation to the top head may be approximated as a small convex surface in a large enclosure. Incropera Equation 13.27 models such geometry.

$$q_{1-11rad} = \sigma A_{11}\varepsilon_{11}(T_1^4 - T_{11}^4)$$

Per the CAD model, A_{11} is 0.356 m². The emissivity of surface 11 is assumed to be 0.5. From EES, T_{11} is calculated to be 869.1 K. Plugging these numbers into the equation yields:

$$q_{1-11rad} = 5.67 \times 10^{-8}(0.356)(0.5)(922^4 - 869.1^4) = 1535\ W$$

This is in agreement with the EES output of 1535 W.

Convection from the environment to the top head is modeled as the top surface of a cooled plate, per Incropera Equation 9.32.

$$\overline{Nu_L} = 0.27Ra_L^{1/4}$$

and

$$q_{1-11conv} = 0.27Ra_L^{1/4}\frac{k_{air}}{L}A_{11}(T_1 - T_{11})$$

We must first determine the value for the Rayleigh number for these conditions.

$$Ra_L = \frac{g\beta(T_1 - T_{11})L_{top}^3}{\nu\alpha}$$

β is $1/T_f$ where T_f is the film temperature ((869.1+922)/2 = 895.55 K). So β is .0011 K^{-1}. From the CAD model, L_{top} = 0.1771 m. From Incropera Table A-4, the viscosity and thermal diffusivity of the air at the film temperature is 102.1 x 10^{-6} m^2/s and 141.9 x 10^{-6} m^2/s, respectively. From the same source, the thermal conductivity of the air is .062 W/m-K. These values provide a Rayleigh number of 2.19 x 10^5.

Plugging these numbers into the convection heat transfer equation:

$$q_{1-11conv} = 0.27Ra_L^{1/4}\frac{k_{air}}{L}A_{11}(T_1 - T_{11}) = 38.5 \, W$$

This agrees very well with the 38.9 W output from EES.

As previously stated, the heat then conducts through the top lid of the cryostat.

$$q_{11-10cond} = \frac{k_{SS}A_{10}(T_{11} - T_{10})}{L}$$

As was the case for path 1, I don't have exact data for the thermal conductivity of the stainless steel, beyond that which I get from EES. However, the matweb data roughly agrees with that of EES, so I will use the EES number for this calculation, so k_{SS} = 23.54 W/m-K. From the CAD Model, A_{10} is .389 m^2 and L_{11} = .025m. From the EES output, T_{10} = 864.8 K. Thus:

$$q_{11-10cond} = \frac{(23.54)(.389)(869.1 - 864.8)}{.025} = 1575 \, W$$

This agrees well with the 1574 W output from EES.

As described earlier, the heat then travels via radiation and convection between the inner surface of the vacuum jacket lid and the outer surface of the inner vessel lid. The radiation transfer is modeled as that between two parallel planes per Incropera Equation 13.24.

$$q_{10-9rad} = \frac{\sigma A_9(T_{10}^4 - T_9^4)}{\frac{1}{\varepsilon_{10}} + \frac{1}{\varepsilon_9} - 1}$$

Per the CAD mode, A = 0.338 m^2. The emissivity of both surfaces is assumed to be 0.5. Per the iterated EES solution, T_9 = 749 K and T_{10} = 864.8 K. Plugging these numbers into the equation results in a heat flow of:

$$q_{10-9rad} = \frac{5.67 \times 10^{-8}(.338)(864.8^4 - 749^4)}{\frac{1}{.5} + \frac{1}{.5} - 1} = 1562.6 \, W$$

This agrees very well with the EES output of 1560 W.

The convection is modeled as that within a rectangular cavity with the bottom cooled ($\tau=180°$). Incropera section 9.8.1 notes that for this condition, heat transfer between the surfaces is purely by conduction, and the Nusselt number is 1, regardless of the Rayleigh number. To model this heat transport, the temperature of the gas is assumed to be the average temperature of the two surfaces.

$$q_{10-9cond} = \frac{k_{air}A_9(T_{10} - T_9)}{L}$$

From the CAD model, L = .156 m. The thermal conductivity (k) of the air at the average temperature of 806.9 K is 0.0576 W/m-K per Incropera Table A.4.

Plugging these values into the equation yields:

$$q_{10-9cond} = \frac{(.0576)(0.338)(864.8 - 749)}{.156} = 14.45\ W$$

This is in excellent agreement with the EES output of 14.43 W.

The heat then conducts through the inner vessel lid.

$$q_{9-8cond} = \frac{k_{ss}A_8(T_9 - T_8)}{L}$$

From the EES solution, T_9 = 749.3 K and T_8 = 742.2K. Again since I lack another reference, and the EES thermal conductivity for stainless steel seems in reasonable agreement with that of matweb.com, I'll rely on the EES value of k_{SS} = 21.84 W/m-K. From the CAD model, L = .025 m and A_8 = .257 m². Plugging these values into the equation yields:

$$q_{9-8cond} = \frac{(21.84)(.257)(749.3 - 742.2)}{.025} = 1594\ W$$

This is in good agreement with the 1574 W EES output.

Finally, the heat radiates to the liquid argon from the inner surface of the inner vessel lid. This radiation is modeled as that between two parallel planes per Incropera Equation 13.24.

$$q_{8-12rad} = \frac{\sigma A_{12}(T_8^4 - T_{12}^4)}{\dfrac{1}{\varepsilon_8} + \dfrac{1}{\varepsilon_{12}} - 1}$$

From the CAD model, A_{12} = .183 m². T_{12} is equal to T_6 at 96.81 K. The emissivity of the surface of the liquid argon vessel lid is assumed to be 0.5, while the emissivity of the liquid argon (and the components within it) is assumed to be 1.0. Thus:

$$q_{8-12rad} = \frac{5.67 \times 10^{-8}(0.183)(742.2^4 - 96.81^4)}{\dfrac{1}{.5} + \dfrac{1}{1} - 1} = 1573.8\ W$$

This is in excellent agreement with the EES output of 1574 W.

Gas evolution and flow out the top of the vessel will prevent effective convective and conductive heat transfer from the inner vessel lid to the liquid argon.

Again, we must note that the steps for this path are in series, thus:

$$q_{11-10cond} = q_{1-11rad} + q_{1-11conv}$$

$$q_{9-8cond} = q_{10-9rad} + q_{10-9cond}$$

$$q_{8-12rad} = q_{9-8cond}$$

$$q_{11-10cond} = q_{9-8cond}$$

Plugging in the values calculated above:

$$1575 \ W \approx 1535 \ W + 38.5 \ W = 1573.5 \ W$$

$$1594 \ W \approx 1562.6 \ W + 14.45 \ W = 1577 \ W$$

$$1573.8 \ W \approx 1594 \ W$$

$$1574 \ W \approx 1594 \ W$$

For the third path, heat is transferred via convection and radiation to the vacuum jacket bottom surface from the environment. It is then conducted across the vacuum jacket wall. Convection and radiation then carry the heat from the inner surface of the vacuum jacket to the outer wall of the inner vessel. Finally, it is conducted across the inner vessel wall into the liquid argon. This is very similar to the model of the first path, except that the Nusselt correlations for this geometry are different.

$$q_{1-13rad} = \sigma A_{13}\varepsilon_{13}(T_1^4 - T_{13}^4)$$

From the CAD model, A_{13} = .271m^2. The emissivity of the vacuum jacket outer surface is assumed to be 0.5. T_1, as before, is 922 K. From the EES solution, T_{13} is 859 K. Plugging in these values:

$$q_{1-13rad} = 5.67 \times 10^{-8}(0.271)(0.5)(922^4 - 859^4) = 1368.9 \ W$$

This is in excellent agreement with the 1368 W output from EES.

Convection to the bottom surface of the cryostat is modeled as the bottom of a heated plate per Incropera Equation 9.32.

$$\overline{Nu}_L = 0.27Ra_L^{1/4}$$

and

$$q_{1-13conv} = 0.27Ra_L^{1/4}\frac{k_{air}}{L}A_{13}(T_1 - T_{13})$$

To validate the calculation, it is first necessary to calculate the Rayleigh number.

$$Ra_L = \frac{g\beta(T_1 - T_{13})L^3}{\nu\alpha}$$

β is $1/T_f$, which is $1/890.5$ K $= .0011$ K^{-1}. The length L is approximated in this case as the bottom area of the vessel divided by the perimeter of the bottom of the vessel, so from the CAD model, 0.271m$^2/1.845$m $= .147$m. At the film temperature (890.5K) the viscosity, thermal diffusivity, and the thermal conductivity are 101.2 x 10^{-6} m^2/s, 140.7 x 10^{-6} m^2/s, and 61.5 x 10^{-3} W/m-K per Incropera, Table A-4. These values yield a Rayleigh number of 1.52 x 10^5.

Plugging these values into the convective heat transfer equation:

$$q_{1-13conv} = 0.27(1.52 \times 10^5)^{1/4}\frac{.0615}{.147}(.271)(922 - 859) = 39.08\ W$$

This is in good agreement with the 38.62 EES output.

The heat then conducts through the bottom wall of the vacuum jacket.

$$q_{13-14cond} = \frac{k_{SS}A_{13}(T_{14} - T_{13})}{L}$$

As before, since the EES value for the thermal conductivity (k) of the stainless seems in reasonable agreement with the single elevated temperature k from matweb.com, I will utilize its value of 23.45 W/m-K. From the CAD model, $T_{14} = 862.6$ K. From the CAD model, L $= .016$ m. Plugging these values into the equation:

$$q_{13-14cond} = \frac{(23.45)(0.271)(862.6 - 859)}{.016} = 1429.9\ W$$

This is in good agreement with the EES output value of 1407 W.

Radiation between the inner surface of the vacuum jacket bottom head and the outer surface of the inner vessel bottom head is approximated at that between two parallel surfaces.

$$q_{14-15rad} = \frac{\sigma A_{15}(T_{14}^4 - T_{15}^4)}{\frac{1}{\varepsilon_{15}} + \frac{1}{\varepsilon_{14}} - 1}$$

From the CAD model, $A_{15} = .203$ m^2. From the EES solution, T_{15} is 106.5 K. The emissivity of the inner surface of the vacuum jacket is assumed to be 0.5, while that of the outer surface of the liquid volume is assumed to be 0.1. Plugging these values into the heat transfer equation:

$$q_{14-15rad} = \frac{5.67 \times 10^{-8}(.203)(862.6^4 - 106.5^4)}{\frac{1}{0.1} + \frac{1}{.5} - 1} = 579\ W$$

This is in good agreement with the 579.1 W EES output value.

Convection between the inner surface of the vacuum jacket bottom head and the outer surface of the inner vessel bottom head may be modeled as that in a horizontal cavity, provided by Incropera Equation 9.49 (when Ra_L is between $3x10^5$ and $7x10^9$, which it is in this scenario).

$$\overline{Nu_L} = 0.069 Ra_L{}^{1/3} Pr^{0.074}$$

and

$$q_{14-15conv} = 0.069 Ra_L{}^{1/3} Pr^{0.074} \frac{k_{air}}{L} A_{15}(T_{14} - T_{15})$$

In order to verify this calculation, we must first calculate the Rayleigh number for this condition.

$$Ra_L = \frac{g\beta(T_{14} - T_{15})L^3}{\nu\alpha}$$

β is $1/T_{avg}$ which is 1/484.55 K = .00206 K^{-1}. From the CAD model, L is .022m. At T = T_{avg} = 484.55K, the viscosity, thermal diffusivity, and thermal conductivity are 36.8 x 10^{-6} m^2/s, 53.8 x 10-6 m^2/s, and 39.6 x 10^{-3} W/m-K, respectively, per Incropera Table A-4. These values yield a Rayleigh number of 8.2 x 10^4. The Prandtl number at this temperature is 0.685, also per Incropera Table A-4. Plugging these values into the convective heat transfer equation yields:

$$q_{14-15conv} = 0.069(8.2 \times 10^4)^{1/3}0.685^{0.074}\frac{.0396}{.022}.203(862.6 - 106.5) = 805\ W$$

This is in good agreement with the EES output of 827.9 W.

Heat then conducts across the inner vessel wall into the liquid argon.

$$q_{15-16cond} = \frac{k_{SS}A_{15}(T_{15} - T_{16})}{L}$$

It should again be noted that the temperature liquid argon is assumed to be 96.81 K ($T_{16}=T_6$)

The average temperature of the stainless steel is 101.655 K. Per NIST, the thermal conductivity (k) of 304 stainless steel at 100K is 9.223 W/m^2-K. From the CAD model, L = .013 m. Plugging these values into the equation yields:

$$q_{15-16cond} = \frac{9.223(0.203)(106.5 - 96.81)}{0.013} = 1395.6\ W$$

This is in good agreement with the EES output of 1407 W.

As in the previous paths, it must be noted that these heat transfer mechanisms are in parallel, and thus:

$$q_{13-14cond} = q_{1-13rad} + q_{1-13conv}$$

$$q_{15-16cond} = q_{14-15rad} + q_{14-15conv}$$

$$q_{15-16cond} = q_{13-14cond}$$

To verify the calculations, we'll plug in the appropriate values and check for approximate equality.

$$1429.9\ W \approx 1368.9\ W + 39.08\ W = 1408\ W$$

$$1395.6\ W \approx 579\ W + 805\ W = 1384\ W$$

$$1395.6\ W \approx 1429\ W$$

These balance equations are satisfied within reason.

Pressure rise in the liquid argon volume under fire condition heat input

As was described previously, assuming that all the heat calculated in the previous section (9015 W) is transferred into the liquid argon, and that the argon is at its saturation point, we can state that all of this heat goes into vaporizing the liquid argon.

The pressure drop calculation was originally performed using EES for quick iteration and accurate thermo-physical properties. However, in the interests of verifying the EES output, the calculations will be re-worked here by hand, with properties sourced from non-EES sources whenever possible.

The energy required to vaporize liquid argon is the latent heat of vaporization, which is 160810 J/kg.

Dividing the total heat input by the latent heat of vaporization yields the mass flow rate of argon that the relief system must transport.

$$\dot{m} = \frac{q_{in}}{L_{vap}}\left[\frac{kg}{s}\right] = .056\left[\frac{kg}{s}\right]$$

Dividing the mass flow rate by the gas density yields the volumetric flow rate. To determine the density of the gas, the gas temperature must be assumed. The gas as it evolves is very cold (just over the temperature of the liquid argon). For the purposes of this calculation, we assume that the gas warms instantaneously to 120K and remains at this temperature up to the vent exit. The gas density from EES of 2.408 kg/m^3 was accepted, as the value makes sense for these conditions vs. the STP density, and I was unable to find a suitable alternative source.

$$\dot{V} = \frac{\dot{m}}{\rho_{gas}}\left[\frac{m^3}{s}\right] = \frac{.056\left[\frac{kg}{s}\right]}{2.408\left[\frac{kg}{m^3}\right]} = 0.023\left[\frac{m^3}{s}\right]$$

Then the dimensions of the vent pipe may be introduced. By dividing the volumetric flow rate by the flow area of the pipe, we can get an average velocity of the gas. After a few iterations, a suitable ID of the vent pipe was determined to be .022 m (1" OD, .065" wall tube). The flow area for such a pipe is .00038 m².

$$V_{avg} = \frac{\dot{V}}{A_{flow}}\left[\frac{m}{s}\right] = \frac{.023\left[\frac{m^3}{s}\right]}{.00038\,[m^2]} = 60.53\,[\frac{m}{s}]$$

We must then compare this velocity to the speed of sound in the gas. The ratio of specific heats (γ) for argon is 1.67. If we assume that the pressure drop calculated by EES is correct, then the average pressure in the relief line is 59671 Pa.

$$V_{sonic} = \left(\frac{\gamma P}{\rho}\right)^{1/2} = \left(\frac{1.67 * 59671}{2.408}\right)^{1/2} = 203.4\,m/s$$

This agrees with the sonic speed value from EES (203.3 m/s).

If the Mach number (the ratio of the average velocity to the velocity of the speed of sound in the gas) is less than or equal to 0.3, then the gas may be treated as incompressible for the calculation (Fox, 1992). Since V_{avg}/V_{sonic} = 0.3, this condition is met, and the gas is considered incompressible.

Next, we must calculate the Reynolds number for the flow. From (Younglove, 1986), the viscosity is .00000972 kg/m-s. This agrees well with the .000009861 kg/m-s value from EES.

$$Re = \frac{\rho V d}{\mu} = 329901\,(fully\ turbulent)$$

The Reynolds number, in combination with the relative roughness of the pipe (assumed to be .004 for these calculations) is used to look up the friction factor f using the Moody Chart. From the Moody Chart in Fox, we get f = .029, which also agrees with the value from EES.

Using these parameters, we may now calculate the loss factor (K factor) for the straight portions of the vent pipe per Crane (Flow of Fluids through Valves, Fittings, and Pipe, 1988). Assuming the length of the straight pipe is 0.5 m (venting into the room), we get:

$$K_{pipe} = \frac{fL_{pipe}}{D_{pipe}} = \frac{.029 * 0.5\,[m]}{.022\,[m]} = .657$$

The contribution of the straight pipe to the overall pressure drop is:

$$\Delta p = \frac{1}{2} K_{pipe} \rho V_{avg}^2 [Pa] = \frac{1}{2}(.657)(2.408)(60.53)^2 [Pa] = 2898 \,[Pa] = .420 \,[psi]$$

This value agrees with the EES output.

In addition to the loss factor from the pipe itself, there are also several other contributors to pressure drop in the vent system. Each of these losses is characterized by a loss coefficient (K value). The pressure drop contributed by each of these features is calculated as for the straight pipe above. The K-values are catalogued in Crane, except for the burst disc, which is from the OSECO PRO+KRGL spec sheet. The sudden expansion within the rupture disc holder is from the nominal tube ID of .022 m to .051m.

Description	K	DP (Pa)	DP (psi)
Sudden constriction to vent tube	0.5	2206	.320
Run flow through tee	0.58	2559	.371
OSECO 1.5" PRO+KRGL rupture disc	0.69	3044	.441
Sudden expansion within the disc holder	0.66	2911	.422
Abrupt exit	1.0	4411	.640

These values all agree with the EES output.

Summing all the contributing pressure drops yields a total vent system pressure drop of 2.61, in agreement with the EES analysis.